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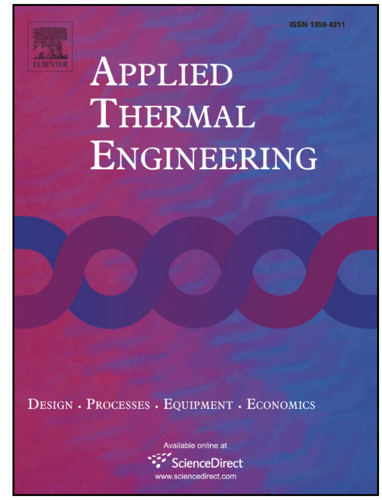

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PII: S1359-4311(18)36226-4
DOI: https://doi.org/10.1016/j.applthermaleng.2019.03.050
Reference: ATE 13479

To appear in: *Applied Thermal Engineering*

Received Date: 10 October 2018
Revised Date: 13 February 2019
Accepted Date: 11 March 2019

Please cite this article as: Z. Li, K. Liang, H. Jiang, Experimental Study of R1234yf as a Drop-in Replacement for R134a in an Oil-free Refrigeration System, *Applied Thermal Engineering* (2019), doi: https://doi.org/10.1016/j.applthermaleng.2019.03.050

Experimental Study of R1234yf as a Drop-in Replacement for R134a in an Oil-free Refrigeration System

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Abstract

R1234yf is a synthetic refrigerant with global warming potential (GWP) of 4 and similar thermodynamic properties to R134a. This paper experimentally compares the performance of R1234yf with R134a in an oil-free vapour compression refrigeration (VCR) system. The oil-free VCR system consisting of oil-free linear compressors, an off-the-shelf condenser and an evaporator with an electric heater avoids the impact of oil lubricant on the heat transfer so that the two refrigerants can be appropriately compared with each other. Experiments for two refrigerants were carried out for compressor strokes of 9-13 mm, operating frequency of 32-38 Hz, pressure ratios of 2- 4, and condenser temperatures of 40-50 °C with refrigerant charge of 250 g. The experimental results show that the coefficient of performance (CoP) of R1234yf is 20% lower than R134a with condenser temperature of 40 °C and evaporator temperature of 0 °C. The volumetric efficiency of R1234yf is 5% lower than R134a with condenser temperature of 40 °C and evaporator temperature of -1.5 °C. Results of evaporator pressure drop, superheat, power input, and cooling capacity are also reported.

Keywords: R1234yf, R134a, Oil-free refrigeration, Cooling capacity, Coefficient of performance, Volumetric efficiency

Nomenclature		S	stroke (mm)
A	piston area (mm^2)	T	temperature (°C)
CFC	chlorofluorocarbon	t	time (s)
CoP	coefficient of performance	V	voltage (V)
DAQ	data acquisition	VCR	vapour compression refrigeration
f	frequency (Hz)	$\dot{W}$	power (W)
GWP	global warming potential		
h	enthalpy (kJ/kg)	*Greek symbol*	
HFC	hydrofluorocarbon	Δ	difference
HFO	hydrofluoroolefin	η	efficiency
I	current (A)		
LVDT	linear variable differential transformer	*Subscripts*	
$\dot{m}$	mass flow rate (g/s)	1	evaporator inlet
ODP	ozone depletion potential	2	suction
P	pressure (bar)	c	cooling
PID	proportional-integral-derivative	cond	condenser
PR	pressure ratio	g	gas

PWM	pulse-width-modulation	in	input
$\dot{Q}$	cooling capacity (W)	suc	suction
R	specific gas constant (J/kg/K)	V	volumetric

1. Introduction

The Montreal Protocol restricted the production and use of chlorofluorocarbons (CFC) as refrigerant due to very high Ozone Depletion Potential (ODP). This led to a shift towards the use of hydrofluorocarbons (HFC). However, HFC still produces significant emissions causing global warming. In order to further reduce the impact on the climate change Global Warming Potential (GWP), traditional HFC such as R134a are being replaced by lower GWP refrigerants. According to latest EU F-gas Regulation, all F-gases with GWP of more than 150 will be banned as the refrigerant or foam blowing agent in any hermetically sealed system from 2022. Several low GWP refrigerants such as R1234yf, R600a, and R717 are considered as potential candidates to replace R134a. Fig. 1 shows the saturation pressure for R1234yf, R134a, R717 and R600a **[1]**. R717 has the highest saturation pressure while R600a has the lowest. The toxicity and the corrosivity restrict the use of R717 for small scale refrigerator. R600a is classified as A3 safety class refrigerant due to high flammability. Low density of R600a means that larger capacity compressor is required. R1234yf and R134a have similar vapour pressure. Table 1 listed the physical, environmental and safety characteristics of R1234yf and R134a. R1234yf has GWP of 4 which is more than 300 times lower than R134a. The latent heat of R1234yf is about 14% lower than R134a at temperature of 30 °C. R1234yf is a lower flammability refrigerant which is qualified to A2L classification in ASHRAE safety group. Hihara **[2]** mentioned that due to low burning velocity, R1234yf can be used safely in air conditioners. Therefore, due to the similar thermal properties, R1234yf has a potential to be used as a drop-in replacement for R-134a in automobile air conditioners without any modification.

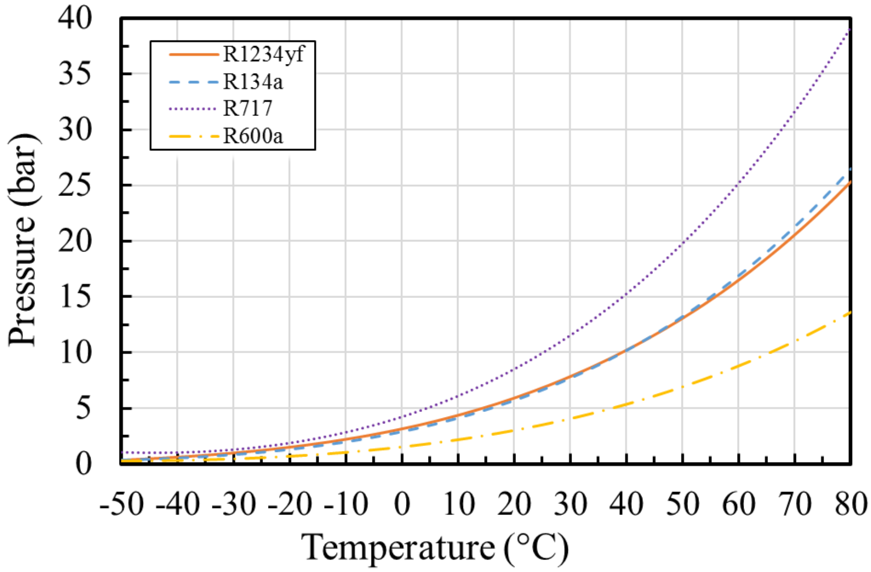

Fig. 1 Saturation pressure against temperature of four refrigerants (R1234yf, R134a, R717 and R600a) adapted from **[1]**

Table 1 Physical, environmental and safety characteristics of R1234yf and R134a adapted from **[3-5]**.

Properties	R1234yf	R134a
Normal boiling point (°C)	-29.4	-26.3
Critical point (°C)	95	102
Critical pressure (bar)	33.8	40.1
Liquid density at 30 °C (kg/m^3)	1075	1187
Vapour density at 30 °C (kg/m^3)	44.1	38
Latent heat at 30 °C (kJ/kg)	148.9	173.1
Molar mass (g/mol)	114	102
GWP (Global warming potential)	4	1430
ODP (Ozone depletion potential)	0	0
ASHEAE safety level	A2L	A1
Lower flammability limit (vol %)	6.2	None
Burning velocity (cm/s)	1.5	None
Auto ignition temperature (°C)	405	770

A number of studies have been conducted by researchers to investigate the drop-in performance of R1234yf in R134a vapour compression refrigeration (VCR) systems. Navarro-Esbri et al. **[6]** tested a VCR system using R1234yf and R134a, which indicated that the coefficient of performance (CoP) is about 19% lower than R134a and the energy performance of R1234yf can be improved significantly by using an internal heat exchanger. Lee and Jung **[7]** examined R1234yf and R134a in a heat pump bench tester, and the experiment shows that these two refrigerants have similar thermodynamic properties and R1234fy can be used as an ideal replacement for mobile air-conditioners with minor modifications. Jankovic et al. **[8]** conducted experiments with a small power refrigerating system to compare the performance between R1234yf, R1234ze, and R134a. The result shows that the cooling capacity and CoP of R1234yf is 9% and 10% lower respectively compared to R134a. Sethi et al. **[9]** presented an experimental evaluation of R1234yf and

R1234ze (E) in a R134a vending machine. The results show that the cooling capacity of R1234yf is 2% lower than R134a. Belman-Flores et al. **[10]** performed an experimental study of R1234yf as a drop-in replacement for R134a in a domestic refrigerator. The results indicate that the power consumption for R1234yf is 4% higher than R134a. Sieres and Santo **[11]** carried out an experiment to study the R1234yf drop-in performance in an R134a small power refrigerating system. The results indicate that the cooling capacity for R1234yf is 6% lower than R134a. Ledesma and Belman-Flores **[12]** built energetic maps using artificial neural networks to predict the CoP of a VCR system. Using these maps the zones with the highest performances were observed to locate the optimal operating conditions. Wang **[13]** reviewed the system performance of R1234yf refrigerant in air-conditioning and heat pump system indicating that the deterioration of R1234yf is around 0-27% depending on operating conditions. Significant difference between R1234yf and R134a system can occur in condenser. The low liquid thermal conductivity of R1234yf can reduce the heat transfer performance particularly in condenser.

Despite a lot of comparative studies on R1234yf and R134a, measurements that have been reported so far all involved oil lubricant for compressors. Oil lubricant inevitably affects the heat transfer in evaporator and condenser thus the overall performance. The absence of lubricant in the system also can prevent the blockage of the tube especially for small diameter heat exchanger. Oil-free VCR system has the potential to use micro-channel heat exchanger to improve the heat transfer. This study compares the performance of R1234yf with R134a in a novel oil-free VCR system over wide range of operating conditions. The elimination of oil lubricant enables comparable test conditions for better evaluating the performance of R1234yf and R134a.

2. Experimental Apparatus

Fig. 2 shows the schematic of the oil-free VCR system and the experimental apparatus. The VCR system consists of two balanced oil-free linear compressors, an off-the-shelf water-cooled coaxial condenser and an evaporator with an electric heater. Two linear compressors operate in opposite direction to reduce vibration. The specifications of components for the oil-free VCR system are listed in Table 2. The hot and pressurised refrigerant gas is released from compressor to condenser. Between the condenser and evaporator, a needle valve is added to adjust the pressure ratio. The liquid refrigerant flows to the evaporator absorbing the heat from the electric heater then goes back to the compressor. A bleed flow loop using PWM (pulse-width-modulation) controlled solenoid valve allows control of body pressure in the linear compressor so that the piston offset can be controlled at zero. The details of the linear compressor can be found in Liang et al. **[14]**.

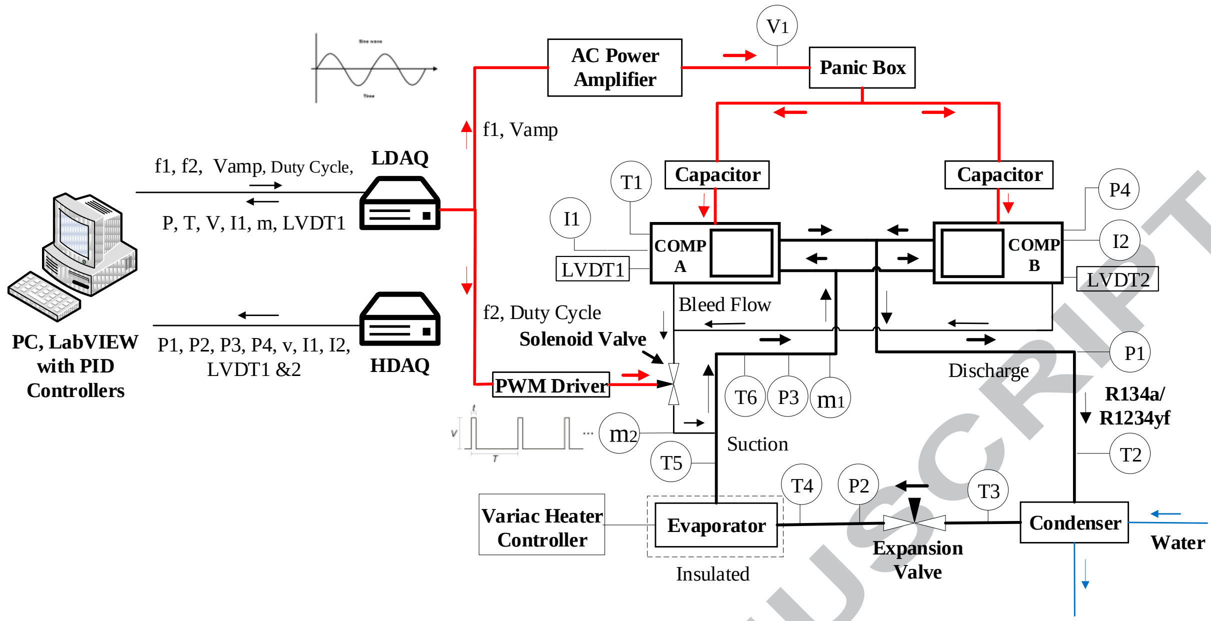

Fig. 2 Schematic of the oil-free VCR system and instrumentation (P: pressure transducer, T: thermocouple, m: mass flow meter, V: voltage sensor, I: current transducer, LVDT: displacement transducer).

Table 2 List of components for the oil-free VCR system.

Components	Specifications
Compressor	Two identical oil-free linear compressors working in opposite, piston diameter of 19 mm, maximum compressor stroke of 14 mm, rated power of 100 W for each
Condenser	Coaxial water-cooled, copper, off-the-shelf, coolant connection diameter of 12.7 mm, refrigerant connection diameter of 16 mm
Expansion valve	Needle valve, stainless steel medium flow high pressure
Evaporator	Copper, electric heater (resistance of 50 Ω), length of 128 cm , inner diameter of 7.9 mm, outer diameter of 12.7 mm
Refrigerant	R134a, R1234yf

Two data acquisition cards of NI USB-6341 were used for both control and data logging in LabVIEW. As for the control system, sinusoidalwaveform signal was generated as anologue output. A PID (proportional-integral-derivative) controller was developed to control the compressor stroke with displacement signal from the LVDT (linear variable differential transformer) displacement transducer. An audio power amplifier amplified the anologue signal to drive the compressors. Two 150 μF capacitors were adopted to reduce the voltage of compressors (improve the power factor). Another PID controller adjusted the duty cycle of the solenoid valve to keep the piston offset at zero. A Variac heater controller was used to adjust the heat into the evaporator. A power meter was used to record the real power of the electrical heater to be compared with cooling capacity that can be calculated from pressure-enthalpy diagram (as shown in Fig. 4). Parameters including pressures (discharge, suction, body, evaporator inlet), temperatures (discharge, condenser, evaporator inlet/outlet, suction, body), and mass flow rates (main flow and bleed flow) were collected as low-speed data acquisition (LDAQ). High-speed data acquisition (HDAQ) collectes data of pressures, voltage, currents, and displacements. According to Nyquist–Shannon sampling theorem, the sampling rate of the HDAQ was 5000 Hz which is 100 times the highest operating frequency of compressor (50 Hz).Table 3 lists the specifications and accuracies of the instruments for the experimental apparatus. The complete experimental apparatus for the oil-free VCR system is shown in Fig. 3.

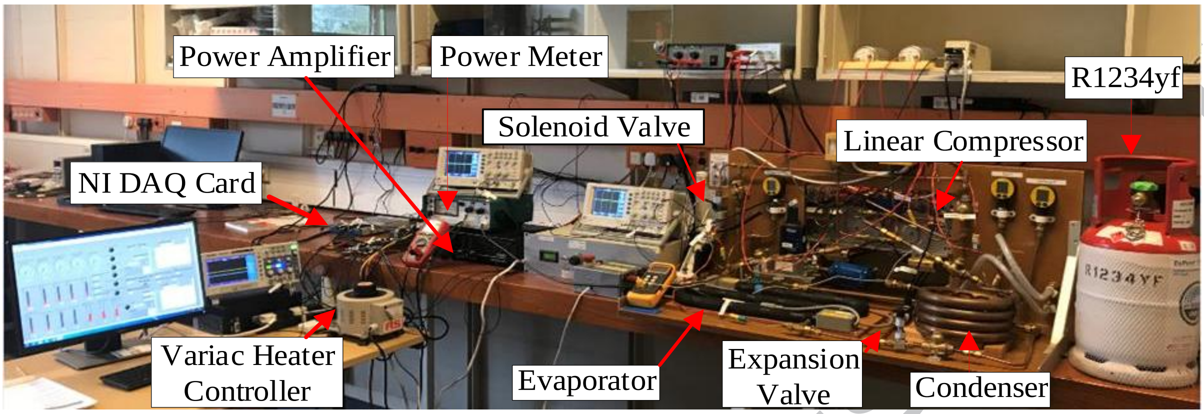

Fig. 3 Complete experimental apparatus for the oil-free VCR system.

Table 3 List of instruments for the oil-free VCR system.

Instruments	Model	Quantity	Accuracy (refer to value)
Data acquisition card	NI USB-6341	2	N/A
Current transducer	LA LEM 25-NP	2	± 0.5 %
Voltage attenuator	Fylde 261HVA HV	1	± 0.5 %
Isolation amplifier	Fylde 4600A	1	± 0.5 %
LVDT	Lucas Schaevitz	2	± 0.025 mm
LVDT signal conditioner	ATA-101	2	N/A
Pressure transducer	DRUCK PMP1400	4	±0.15 %
Capacitor	EPCOS B32361	2	± 5 %
AC power amplifier	Vonyx VXA-2000 (class A)	1	± 1.2dB
Thermocouple	K-type	8	± 1.5 °C
Main mass flow meter	Hastings HFM-201	1	± 1 %
Bleed flow meter	Tylan FM-360	1	± 1 %
Oscilloscope	RS Pro IDS1000 Series IDS1072AU	3	N/A
Power meter (heater)	Electronic Wattmeter EW604	1	< 2.5% (50Hz, unity power factor, 25 °C)

Experiments for the two refrigerants were carried out at different compressor strokes, pressure ratios, frequencies, and condenser temperatures as shown in Table 4. The charge is same for both refrigerants. Before measurements, the compressor was heated by resistors to over 35 °C so that no refrigerant condenses in the compressor. Linear compressor can operate at resonance to reduce the input current required. Operating frequency was manually adjusted in LabVIEW for each test condition to ensure resonance. The resonant frequency was calculated assuming a linear gas spring **[14]**.

Table 4 Test conditions for two refrigerants in the oil-free VCR system.

Refrigerant	R1234yf, R134a
Charge (g)	250
Pressure ratio	2.0, 2.5, 3.0, 3.5, 4.0
Compressor stroke (mm)	9, 10, 11, 12, 13

Condenser temperature (°C)	40, 45, 50
Operating frequency (Hz)	32-38
Suction temperature (°C)	20-30
Compressor body temperature (°C)	>35
Ambient temperature (°C)	22

3. Results and Discussions

3.1 P-h Diagram and Evaporator Temperature

Eight-two steady-state tests were conducted for the two refrigerants. The evaporator saturation temperature is calculated from the evaporator inlet pressure. Fig. 4 shows the pressure-enthalpy (p-h) diagram of R1234yf and R134a for a pressure ratio of 3.5 and a compressor stroke of 13 mm at a condenser outlet temperature of 40 °C. R134a gives a cooling capacity of 171 W while R1234yf only gives 125 W. The cooling capacity of R1234yf is 27% lower than R134a mainly due to the smaller enthalpy difference of R1234yf though the compression work is similar (35 W). The discharge and suction pressure for R1234yf is 0.23 bar and 0.14 bar higher than R134a, respectively. Higher discharge and suction pressure of R1234yf result in a higher in-cylinder pressure thus higher seal leakage loss and lower efficiency of linear compressor.

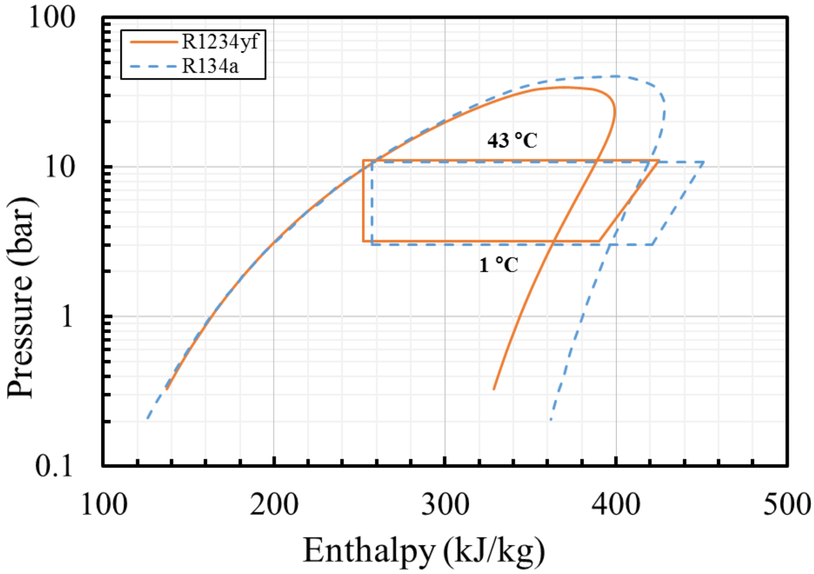

Fig. 4 Pressure-enthalpy (p-h) diagram of R1234yf and R134a for pressure ratio of 3.5, compressor stroke of 13 mm and condenser temperature of 40 °C.

Fig. 5 shows the evaporator temperature against compressor stroke with pressure ratios from 2.0 to 4.0, at a fixed condenser temperature of 40 °C. Evaporator temperature decreases with pressure ratio with a fixed condenser temperature. The evaporator temperature ranges from -3 °C to 25 °C. For fixed pressure ratio, the evaporator temperature hardly varies with the compressor stroke which was adjusted for cooling capacity modulation. For the same operating condition, the evaporator temperature is very close between R134a and R1234yf. The maximum difference is only 1.5 °C which can be attributed to the thermocouple accuracy (1.5 °C). Since evaporator temperatures are similar for both refrigerants at various operating conditions, the subsequent parameters can then be compared to evaluate the two refrigerants.

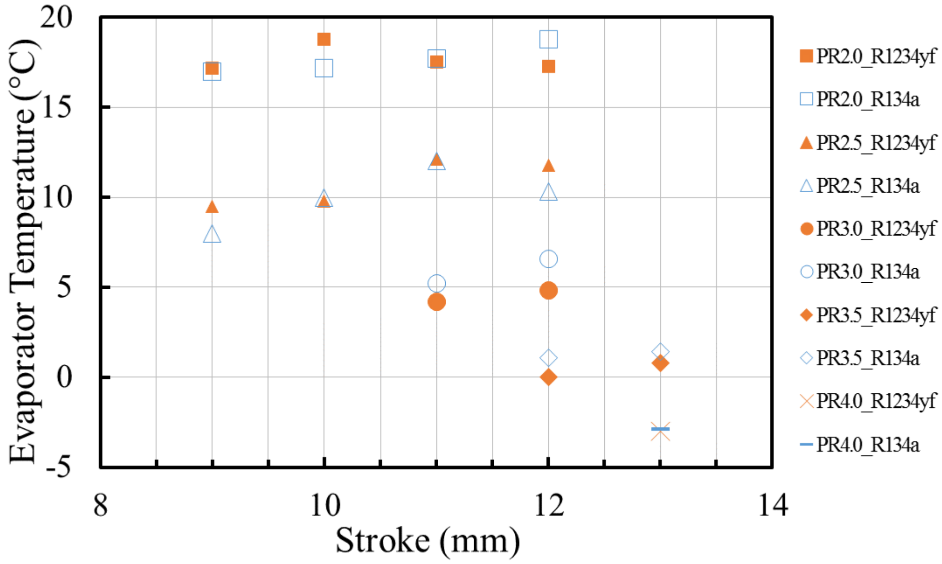

Fig. 2 Evaporator temperature against compressor stroke for pressure ratios (PRs) of 2.0 to 4.0, at condenser temperature of 40 °C.

Fig. 6 shows the superheat against the evaporator temperature for R1234yf and R134a with pressure ratios of 2.0 to 4.0 at condenser temperatures of 40 °C and 50 °C. The superheat for both refrigerants decreases with increasing evaporator temperature. For a given evaporator temperature, R1234yf has higher superheat than R134a. For a condenser temperature of 50 °C, the average difference of superheat between the two refrigerants is about 6 °C. For lower condenser temperature, the difference increases with evaporator temperature. A higher superheat of R1234yf has a negative influence on mass flow rate due to the reduction of the refrigerant vapour density. A higher superheat results in a higher in-cylinder temperature thus higher heat transfer loss via cylinder wall, more compression work and thus lower CoP.

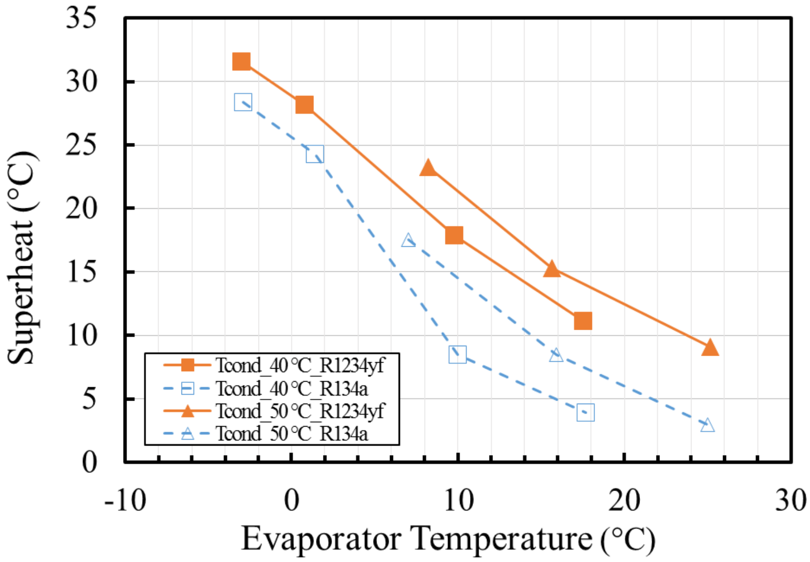

Fig. 6 Superheat against evaporator temperature for R1234yf and R134a at condenser temperatures of 40 °C and 50 °C.

3.2 Resonant Frequency and Mass Flow Rate

Fig. 7 shows the resonant frequency of the oil-free VCR system using R1234yf and R134a with pressure ratios from 2.0 to 3.0 at a fixed condenser temperature of 40 °C. For both refrigerants, a higher pressure ratio leads to a higher resonant frequency due to higher induced gas spring stiffness. For a fixed pressure ratio, higher compressor stroke causes lower gas spring thus lower resonant frequency. Generally, R1234yf has higher resonant frequency than R134a. This is because the discharge pressure is higher for R1234yf owing to higher superheat (shown in Fig. 6).

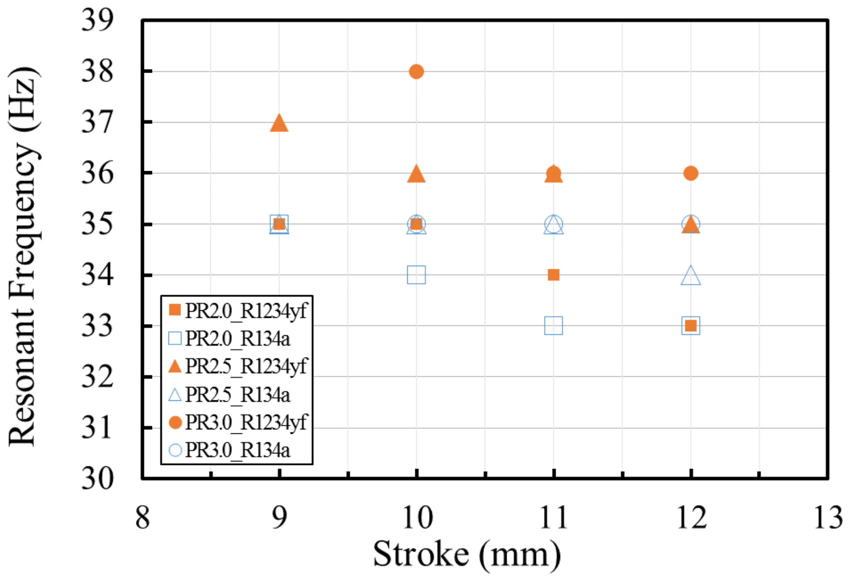

Fig. 7 Resonant frequency against compressor stroke of the oil-free VCR system using R1234yf and R134a with various pressure ratios at a condenser temperature of 40 °C.

Fig. 8 shows the mass flow rate of R1234yf and R134a varying with the compressor stroke for pressure ratios of 2.0 to 3.5 at a fixed condenser temperature of 40 °C. It can be seen that for a fixed compressor stroke, the mass flow rate decreases as the pressure ratio increases. For a fixed pressure ratio, the mass flow rate of R1234yf and R134a both increase as the compressor stroke increase thus cooling capacity. Overall, R1234yf provides an average 5%higher mass flow rate than R134a due to the high vapour density and resonant frequency. The vapour density of R1234yf is 14% higher than R134a as mentioned in Section 1. High seal leakage loss due to the high in-cylinder pressure deteriorates the mass flow rate of R1234yf. At pressure ratio of 2.5 of compressor stroke of 12 mm, the mass flow rate of R1234yf is 0.36 g/s (16%) higher than R134a.

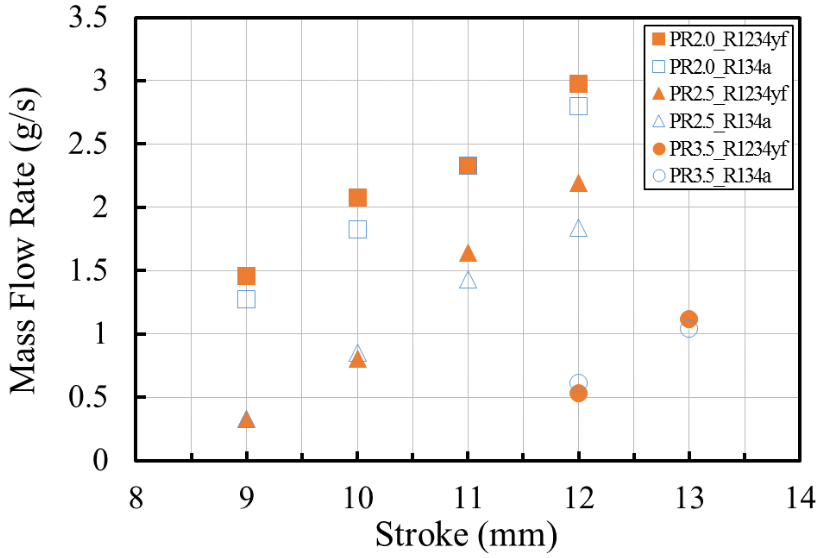

Fig. 8 Mass flow rate against compressor stroke using R1234yf and R134a for pressure ratios of 2.5 to 3.5 at a fixed condenser temperature of 40 °C.

Fig. 9 illustrates the specific mass flow rate against condenser temperature using R1234yf and R134a for pressure ratios of 2.5 and 3.5. It can be seen that for a fixed condenser temperature, specific mass flow rate decreases as the pressure ratio increases due to the decrease of volumetric efficiency. For a fixed pressure ratio, the specific mass flow rate for two refrigerants decrease as the discharge pressure increase thus electrical power input. The decrease of mass flow rate has degraded specific mass flow rate.

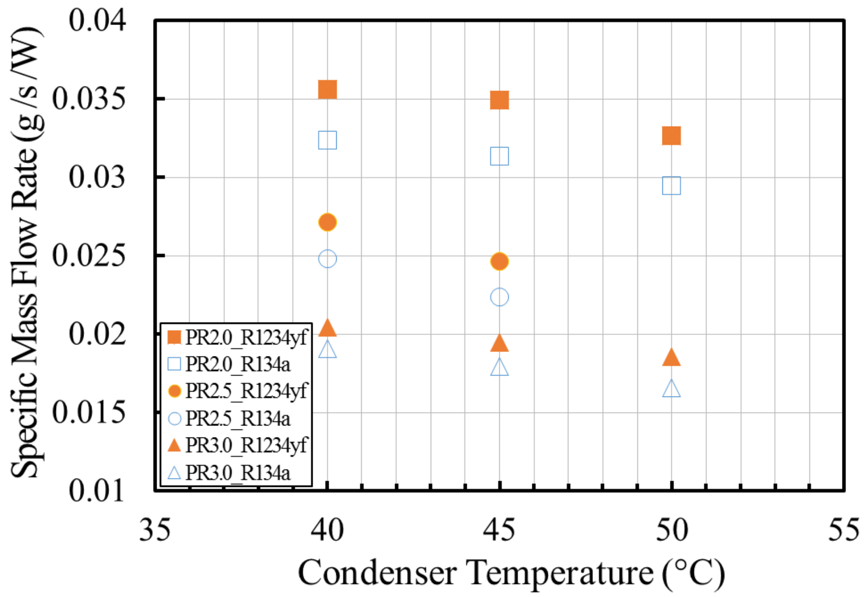

Fig. 9 Specific mass flow rate against condenser temperature using R1234yf and R134a for pressure ratios of 2.5 and 3.5.

3.3 Electrical Power Input and Evaporator Pressure Drop

The electrical power input (P_{in}) into the linear compressor was calculated as below:

$$\dot{W}_{\text{in}} = \frac{1}{t}\int_0^t V \cdot I dt \tag{1}$$

where t is the period, V is the voltage, I is the current.

Fig. 10 shows the power input varying with the mass flow rate for R1234yf and R134a for pressure ratios from 2.0 to 3.5 at a fixed condenser temperature of 40 °C. It can be seen that the power input increases very linearly with the mass flow rate due to increasing compressor stroke at a fixed pressure ratio. Overall, due to the higher vapour density, R1234yf requires 6-15% lower power input to achieve a same mass flow rate for R134a. The lower power input for R1234yf results in a lower copper loss because of a lower input current. It is interesting to see that the rate of increasing is nearly same for both refrigerants at various pressure ratios. At a fixed pressure ratio of 2.0 and a mass flow rate of 2 g/sthe power input for R1234yf is 16% lower than R134awith average difference of 7 W. However, at a fixed pressure ratio of 3.5, the different of power input is negligible.

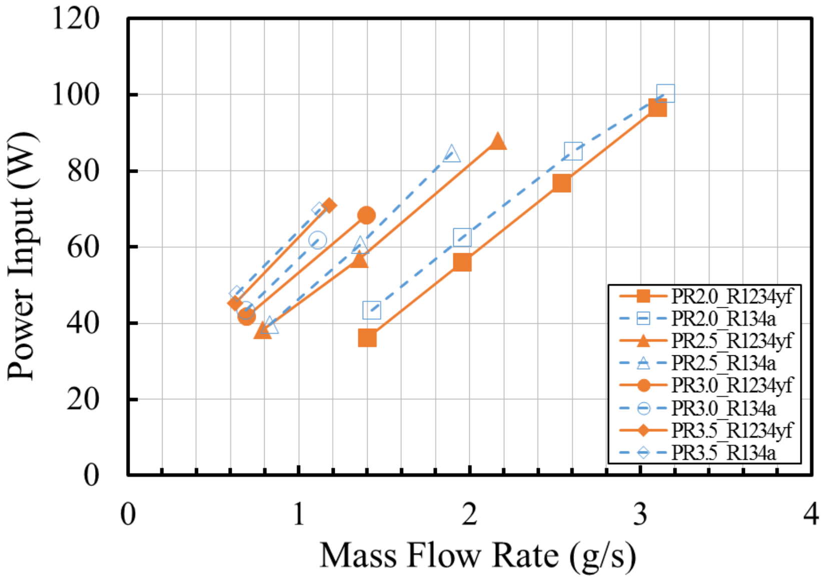

Fig. 10 Power input against mass flow rate for R1234yf and R134a for pressure ratios of 2.5 to 3.5 at a fixed condenser temperature of 40 °C.

Fig. 11 shows that the evaporator pressure drop as a function of the mass flow rate for R1234yf and R134a at condenser temperatures (T_{cond}) of 40 °C, 45 °C, and 50 °C. It can be seen that the evaporator pressure drop for R1234yf is higher than R134a for same mass flow rate. This may due to the higher friction loss and vapour density of R1234yf. For a mass flow rate of 2.3 g/s at a fixed condenser tempreature of 45 °C, the pressure drop across the evaporator for R1234yf is 0.016 bar higher than R134a. Higher pressure ratio leads to higher pressure drop. Higher mass flow rate will also cause much higher pressure drop. This is due to a larger friction of R1234yf than R134a.

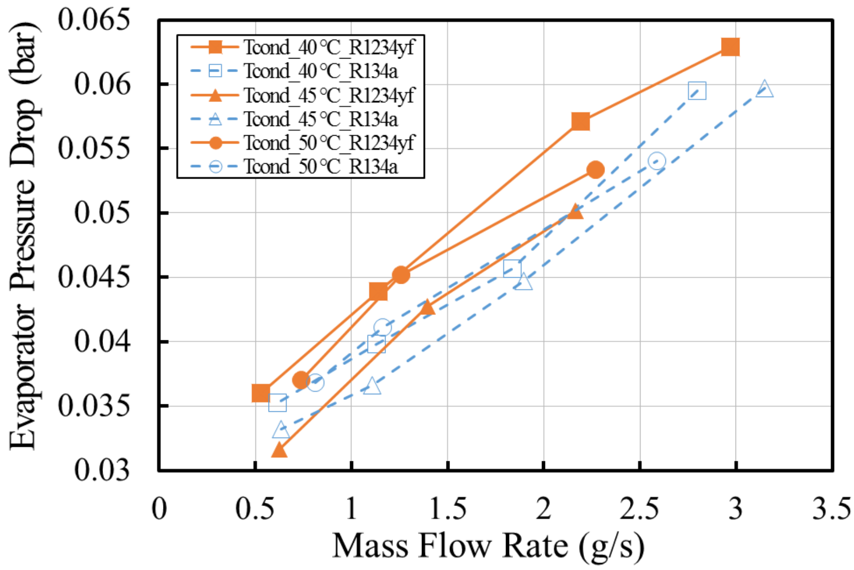

Fig. 11 Evaporator pressure drop against mass flow rate for R1234yf and R134a at condenser temperatures of 40 °C, 45 °C, and 50 °C.

3.4 Volumetric Efficiency

The volumetric efficiency was calculated according to the following equation:

$$\eta_V = \frac{\dot{m} R_g T_{suc}}{SAf P_{suc}} \tag{2}$$

where A is the area of piston, f is the operating frequency, S is the compressor stroke, T_{suc} is the temperature at the compressor inlet, P_{suc} is the pressure at the compressor inlet, R_g is the specific gas constant and $\dot{m}$ is the mass flow rate.

Fig. 12 shows the volumetric efficiency against the evaporator temperature for R1234yf and R134a at condenser temperatures of 40 °C, 45 °C, and 50 °C. It can be seen that the volumetric efficiency for both refrigerants increases linearly with the evaporator temperature due to decreasing pressure ratio. Higher condenser temperature causes lower mass flow rate and thus lower volumetric efficiency for both refrigerants. At a fixed condenser temperature of 40 °C, the volumetric efficiency of R1234yf is 1-4% lower than R134a due to the higher suction pressure and resonant frequency of R1234yf as mentioned in Section 3.1 and 3.2 though the mass flow rate of R1234yf is slightly higher than R134a.

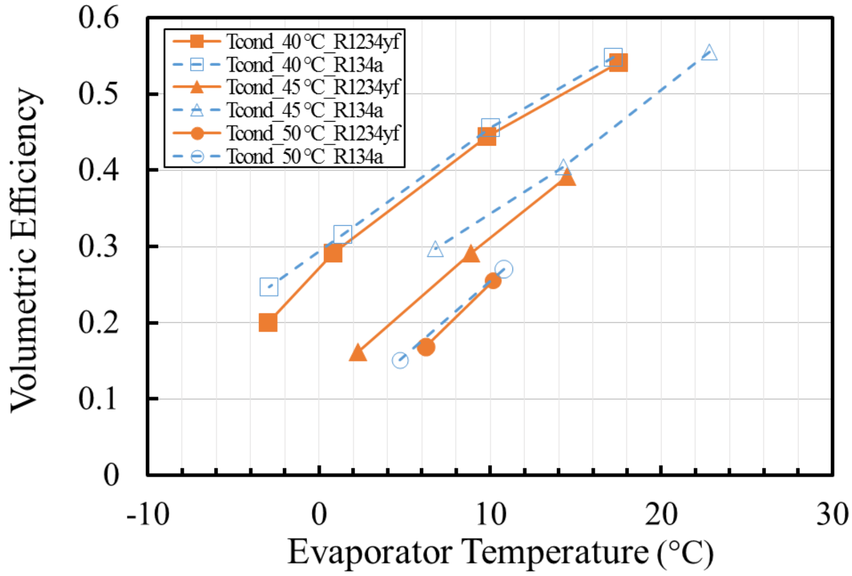

Fig. 12 Volumetric efficiency against evaporator temperature for R1234yf and R134a at condenser temperatures of 40 °C, 45 °C, and 50 °C.

3.5 Cooling Capacity and CoP

The cooling capacity was calculated according to the following equation:

$$\dot{Q}_c = \dot{m}(h_2 - h_1) \quad (3)$$

where h_1 is the enthalpy of refrigerant at evaporator inlet, h_2 is the enthalpy of refrigerant at suction.

The CoP is defined as the ratio of the cooling capacity to the electrical power input:

$$CoP = \frac{\dot{Q}_c}{P_{in}} \quad (4)$$

Fig. 13 shows the cooling capacity against the evaporator temperature for R1234yf and R134a at condenser temperatures of 40 °C, 45 °C, and 50 °C. The cooling capacity for both refrigerants increase with evaporator temperature. A higher condenser temperature tends to have a lower cooling capacity for both refrigerants due to a lower mass flow rate. The cooling capacity for R1234yf is 5-20% lower than R134a. This is due to the lower latent heat of R1234yf in comparison with R134a. The difference of cooling capacity between the two refrigerants doesn't change much with the increase of condenser temperature. At evaporator temperature of -3 °C and condenser temperature of 40 °C, the cooling capacity for R1234yf and R134a is 93 W and 118 W respectively. To produce the same amount of cooling capacity for a fixed evaporator and condenser temperature, compressor needs to operate at higher compressor stroke or displacement (for conventional compressors). This could be a major modification if R1234yf replaces R134a in a refrigeration system.

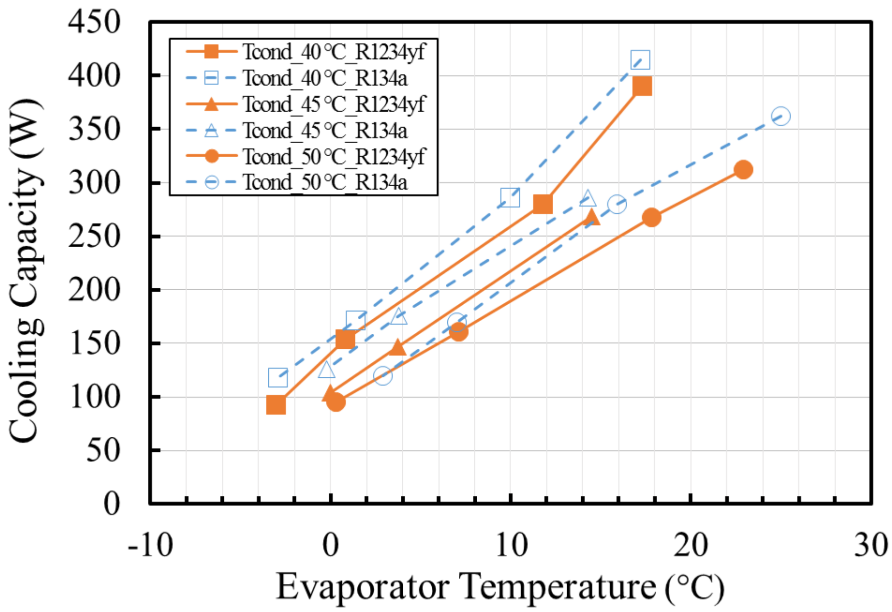

Fig. 13 Cooling capacity against evaporator temperature for R1234yf and R134a at condenser temperatures of 40 °C, 45 °C, and 50 °C.

Fig. 14 shows the CoP against evaporator temperature for R1234yf and R134a at condenser temperatures of 40 °C, 45 °C, and 50 °C. For both refrigerants, the CoP increases with evaporator temperature. R1234yf has lower CoP than R134a due to the low cooling capacity and volumetric efficiency. The CoP at evaporator temperature of -3 °C and condenser temperature of 40 °C for R1234yf and R134a is 1.8 and 2.3 respectively. The CoP at evaporator temperature of 17 °C and condenser temperature of 40 °C for R1234yf and R134a is 4.4 and 4.8 respectively. At condenser temperature of 40 °C, the CoP of R1234yf is 5-20% lower than R134a. At a fixed condenser temperature of 50°C, the CoPs of R1234yf are almost same as R134a.

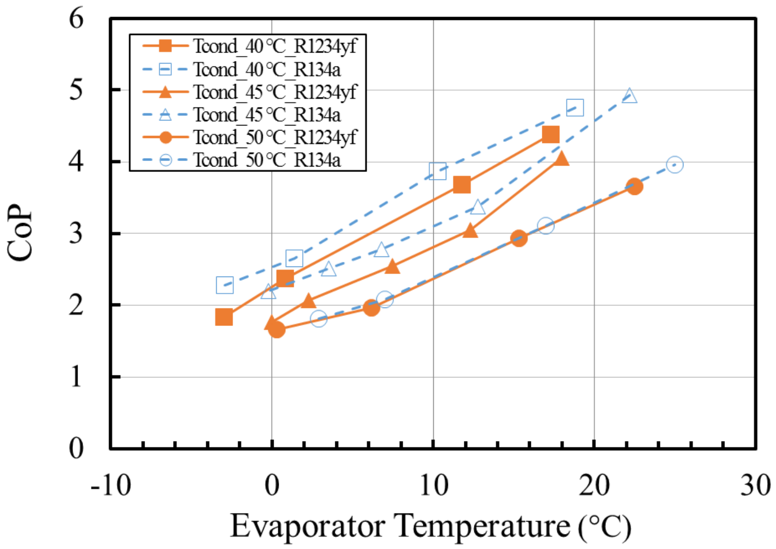

Fig. 34 CoP against evaporator temperature for R1234yf and R134a at condenser temperatures of 40 °C, 45 °C, and 50 °C.

Fig. 15 shows the cooling capacity and CoP against condenser temperature for R1234yf and R134a with evaporator temperature of 5 °C. Both cooling capacity and CoP decrease linearly with increasing condenser temperature due to reduction of the enthalpy between evaporator inlet and outlet for R1234yf and R134a. Moreover, increase of electrical power input has degraded CoP. The CoP of R1234yf is 10-25% lower than R134a, while the cooling capacity of R1234yf is 10-30% lower than R134a. It is worth mentioning that with increasing condenser temperature, the difference of CoP between R1234yf and R134a decreases as R1234yf is less sensitive to condenser temperature.

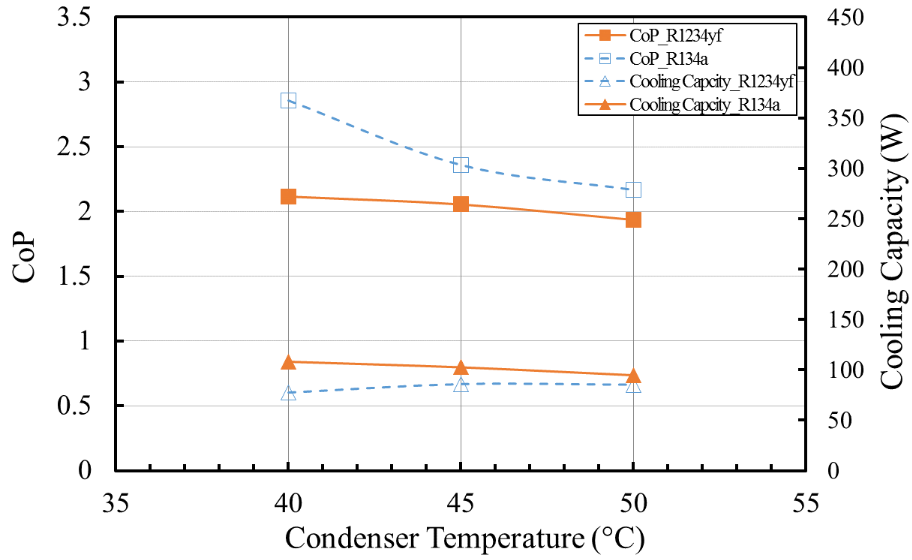

Fig. 15 Cooling capacity and CoP against condenser temperature for R1234yf and R134a with evaporator inlet temperature of 5 °C.

3.6 Comparison with Literature

Table 5 lists the experimental variation of R1234yf for cooling capacity and CoP taking R134a as the baseline. At a condenser temperature of 40 °C and an evaporator temperature of 17 °C, R1234yf achieves the highest CoP of 4.4 while R134a achieves a CoP of 4.8. For the conditions shown in Table 5, the cooling capacity and CoP of R1234yf is 5-25% and 3-20% lower than R134a. The difference of CoP between two refrigerants is lower for high condenser temperatures. Table 6 lists the R1234yf system performance from literature. The general trends of the results in this work agree very well with those obtained by other researchers **[6, 7, 9, 15-21]**. The oil-free VCR system tends to achieve higher CoPs comparing with traditional VCR systems due to the absence of lubricant and reduction of mechanical friction loss. For instance, at a fixed condenser temperature of 45 °C and a fixed evaporator temperature of 0 °C, CoP can be improved about 8% using oil-free VCR system comparing with the results presented by Sanchez et al. **[16]** using traditional reciprocating compressor. At a fixed condenser temperature of 40 °C and a fixed evaporator temperature of 0 °C, R1234yf and R134a achieves a CoP of 2.36 and 2.51, respectively, in this work while R1234yf and R134a achieves a CoP of 2.2 and 2.4, respectively, using crank-driven compressor reported by Mota-Babiloni et al. **[20]**. Moreover, due to elimination of oil lubricant which affects the heat transfer and pressure drop, the results in this work could be better comparison between R134a and R1234yf. Zilio et al. **[15]** mentioned that enhancing 20% of the condenser and 10% of the evaporator surface area could overtake the CoP value than the baseline R134a for cooling capacities. However, simply increasing the surface and diameter of traditional heat exchanger is not attractive for modern refrigeration device.

Micro-channel and internal heat exchanger can be potential choice for further improvement of system using R1234yf. Large displacement compressor for R1234yf will be needed as well to produce a similar cooling capacity to R134a.

Table 5 Experimental variation for power input, cooling capacity, and CoP taking R134a as baseline with various pressure ratios, condenser temperatures and a fixed compressor stroke of 12 mm

Pressure ratio	Condenser temperature (°C)	Diff. Cooling capacity (%)	Diff. CoP (%)
2.5	40	-11%	-15%
3.0	40	-22%	-20%
3.5	40	-20%	-18%
4.0	40	-22%	-20%
2.5	45	-16%	-14%
3.0	45	-8%	-11%
3.5	45	-18%	-16%
4.0	45	-18%	-20%
2.5	50	-25%	-8%
3.0	50	-12%	-10%
3.5	50	-5%	-3%
4.0	50	-20%	-10%

Table 6 System performance using R134a and R1234yf from related literature

Authors	System	Test conditions	Conclusions
Navarro et al. **[6]**	Compressor: open type reciprocating compressor Condenser: shell-and-tube condenser Evaporator: shell-and-tube evaporator	T_{cond}: 40~60 °C T_{evap}: -8~7 °C	The cooling capacity of R1234yf is about 9% lower than R134a in the test range. The CoP using R1234yf is 5%~30% lower than R134a in the test range.
Lee and Jung **[7]**	Compressor: open type compressor Condenser and evaporator: double tube commercial pipes	T_{cond}: 41 °C and 45 °C T_{evap}: -7 °C and 7 °C	The CoPs for R1234yf are 0.8%-2.7% lower than R134a.
Sethi et al. **[9]**	Small refrigerator	T_{cond}:30-40 °C T_{evap}: 2 °C	The cooling capacity and CoP for R1234yf is 2% and 3% lower than R134a.
Zilio et al. **[15]**	Compressor: variable rotation speed compressor Condenser: brazed plate heat exchanger	Evaporator air inlet 35 °C and 40% relative humidity. Condenser air inlet: 35 °C	The cooling capacity and CoP of the drop-in R1234yf system are considerably lower than the

	Evaporator: laminated plate		baseline R134a system.
Sánchez et al. **[16]**	Compressor: hermetic compressor Condenser: brazed plate heat exchanger Evaporator: brazed plate heat exchanger	T_{cond}: 25 °C, 35 °C, 45 °C T_{evap}: 0°C	The cooling capacity and CoP for R1234yf is 4.5% and 10% lower than R134a respectively.
Direk et al. **[17]**	Compressor: belt-driven swash-plate Compressor Condenser: parallel-flow Evaporator: laminar micro-channel	T_{cond}: 30 °C, 35 °C T_{evap}: 7 °C	The cooling capacity and CoP for R1234yf is 13.9~20.4% and 7.5~16.5%% lower than R134a respectively.
Llan-Gomez and Garcia-cascales **[18]**	Compressor: reciprocating Embraco compressor Condenser: compact heat exchanger Evaporator: Plate heat exchanger	T_{cond}: 20 °C, 30 °C, 35 °C, and 40 °C T_{evap}: 7 °C	The volumetric efficiency for R1234yf is 4% lower than R134a.
Rangel-Hernandez et al. **[19]**	Domestic refrigerator	T_{cond}: 40 °C T_{evap}: -20 °C to -5 °C	The CoP for R1234yf is 20% lower than R134a.
Mota-Babiloni et al. **[20]**	Compressor: reciprocating open-type compressor Condenser: shell-and-tube condenser Evaporator: shell-and tube evaporator	T_{cond}: 37 °C, 47 °C, and 57 °C T_{evap}: -13 °C, -3 °C, and 3 °C	The CoP for R1234yf is 3-11% lower than R134a.
Mendoza-Miranda et al. **[21]**	Compressor: variable speed reciprocating open type compressor lubricated with polyolester oil Condenser: shell and smooth tube condenser Evaporator: micro-fin tubes evaporator	T_{cond}: 37 °C to 57 °C T_{evap}: -13 °C, -3 °C, and 3 °C	The CoP for R1234yf is 8-13% lower than R134a.

3.7 Experimental Uncertainty

Pressures, temperature, stroke, current, voltage, and mass flow rate were measured during the experiments. Typically, a set of readings was taken every 15 minutes to allow time for thermal equilibrium to be attained. The measurements of pressure, stroke, and temperature have absolute uncertainties of 0.015bar, 0.025mm, and 0.5 °C. The current transducer, voltage transducers, and mass flow rate have accuracies of 0.5%, 0.5%, and 1%, respectively. The combined uncertainties of the calculated values were calculated using a 95% confidence interval. The cooling capacity, CoP, specific mass flow rate, and volumetric efficiency have relative uncertainty of 1%, 1.3%, 1.9%, and 0.3%, respectively.

4 Conclusions

In this study, the system performance of the low GWP refrigerant R1234yf as a drop-in replacement for R134a in an oil-free VCR system was presented for wide range of operating conditions. Generally R1234yf deteriorates the performance if it replaces R134a. Further modification of refrigeration system is needed for use of R1234yf including higher compressor stroke or displacement. Key findings from the experiments are listed as below:

(1) For given pressure ratio and compressor stroke, the resonant frequency of R1234yf is higher than R134a due to higher superheat.
(2) At fixed pressure ratio, the mass flow rate of R1234yf is 5% higher than R134a. The power input for R1234yf is 6-15% lower than R134a for given mass flow rate.
(3) The evaporator pressure drop for R1234yf is higher than R134a for given mass flow rate due to higher friction.
(4) With the increase in evaporator temperature, the volumetric efficiency for both refrigerants increases and higher condenser temperature tends to have a lower volumetric efficiency.
(5) At condenser temperature of 40 °C, the CoP of R1234yf is 5-20% lower than R134a depending on the evaporator temperature and compressor stroke. The CoP increases linearly with decreasing condenser temperature. However, the CoP of R1234yf is less sensitive to condenser temperature.

Acknowledgement

The Research Development Fund from the University of Sussex (UA016-05) for supporting the instrumentation of the VCR system is acknowledged. The authors are also grateful to Prof Richard Stone, Dr Mike Dadd and Paul Bailey at the University of Oxford for the prototype oil-free linear compressor. The authors are grateful to Andy White and Barry Johnson at the University of Sussex for the lab support.

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Highlights

- R1234yf was compared with R134a in a novel oil-free refrigeration system
- For given pressure ratio, mass flow rate of R1234yf is higher than R134a
- Evaporator pressure drop for R1234yf is higher than R134a due to higher friction
- CoP of R1234yf is 20% lower than R134a when condenser temperature is 40°C
- Specific mass flow rate of R1234yf decreases with increasing condenser temperature